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Load path uncertainty in a wood structure and the effect on structural reliability

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ABSTRACT

The roof truss bearing points of a light-framed wood house were instrumented with load cells. It was found that under dead load alone, symmetric and theoretically identical truss reactions have significant variation. A similar degree of reaction discrepancy was found under the application of uplift pressures caused by hurricane winds. Analysis revealed that the majority of this discrepancy is caused by inherent uncertainties in load path. Although uncertainties in load magnitude and material resistance are accounted for in design by use of appropriate load and resistance factors, load path is generally taken to be deterministic. In this study, load path uncertainty in a test structure is statistically quantified and the effect on the reliability of wood structural members is investigated. Although large uncertainties in reactions were present, it was found that the resulting influence on reliability was modest, with decreases in component reliability index ranging from 5% to 15%.

1. Introduction

Uncertainties in loads and resistance have been formally recognized for decades in structural design. A significant body of information has been obtained over the years from empirical studies and analysis to estimate statistical parameters for various structural loads, such as dead load, occupancy live load, wind, earthquake, snow, and rain, among others. Similar parameters have been developed to characterize uncertainty in structural component resistance to moment, shear, axial tension and compression, and other force effects (see for example [1], and numerous others). This information was used to develop appropriate load and resistance factors in the various design standards for concrete, steel, wood, and other structural materials [2–5]. The study of wood structures has evolved significantly in the past 20 years, but only recently have reliability concepts taken a bigger role in the research of wood structures. A reliability-based design standard for wood structures was developed in 1988 with the publication of the ASCE and the National Forest Products Association's (NFPA) *Load and Resistance Factor Design for Engineered Wood Construction* [6]. The most recent version of the *National Design Specifications for Wood Construction* [5] incorporates both allowable stress design (ADS) and load and resistance factor design (LRFD).

Various studies have examined the reliability of wood structures for the general development of reliability-based design [7–14], as well as specific loads, components, and systems such as high wind events [15–18], wall and roof systems [10,19–23], sheathing panels [24–28]; and shear walls [29–33]. The probabilistic models developed from this body of work for structural loads and resistance account for variations in load magnitude, frequency, and location, as well as variation in material strength and geometry that lead to uncertainty in component resistance. However, they do not directly account for the uncertainty of interest in this study: uncertainty in how load is distributed throughout the structural system; i.e. uncertainty in load path.

Various modeling and experimental approaches have been suggested to predict and characterize the behavior of wood structural systems. Tuomi [34] discussed the full-scale load testing of structures, emphasizing the effect of variability of material, connection properties, orthotropy, and relative humidity of wood. Liu et al. [35] suggested the need for developing better analytical procedures to predict the behavior of light-frame wood structures, while soon after, Kasal and Leichti [36] introduced a nonlinear finite-element model for light-frame stud walls, and later, investigated a full-scale light frame wood structure and presented a finite element model for predicting deformations and load distribution [37]. Other modeling advancements include Collins et al. [38], who suggested a 3-D finite element modeling approach to investigate various aspects of light frame building behavior under static and dynamic loading. Later, Asiz et al. [39] developed an advanced 3-D modeling approach to study the progressive collapse of wood structures, while Martin [40] used finite element analysis to study load paths through a wood structure. Doudak et al. [41] modeled

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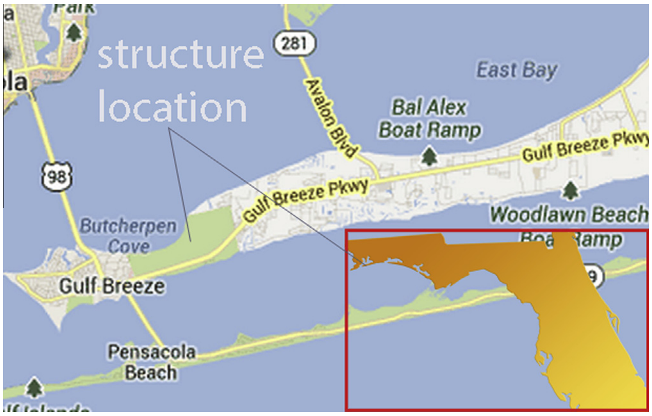

Fig. 1. Experimental house location.

wood light frame shear walls with openings using finite element models, and later demonstrated in a full-scale testing that system effects dominate the response for vertical and lateral loads, including the importance of considering the three-dimensional behavior, which originates from the relative stiff interconnection of roof, wall, and floor platform substructures [42].

The Forest Products Laboratory (US Dept. of Agriculture, Madison, WI) sponsored the construction of a light-framed wood house on the Florida coastline [43]. During construction, the roof structure was instrumented with pressure gages, and load cells were placed between the connections of the roof structure and the supporting walls below.

Although the intended purpose of the structure was to measure wind loads, significant differences (greater than 50% in many cases) were found among symmetrically placed load cell reactions due to dead load alone. Similarly large discrepancies were found between the reactions caused by the application of uplift pressures caused by hurricane winds and those predicted from analysis when the same measured uplift pressures were applied on the analytical model. Although some discrepancy is expected, differences of this magnitude raised concerns about the predictability of wood structural behavior using deterministic modeling approaches.

Although a single case study is insufficient to generalize, results can be studied to raise issues of concern that may be relevant to other similar structures. The objective of this study is to identify the possible cause of this reaction uncertainty, to quantify the uncertainty in the load path (i.e. roof reactions) in the study structure, and to examine the potential effects on the reliability of wood components in general that a similar uncertainty in load path would entail.

2. Field structure

The data are taken from a full-scale instrumented residential building that satisfies the structural construction requirements of the 2005 International Building Code (IBC) standards [44]. Sponsored by the Forest Products Laboratory, the structure was built by a local contractor using standard practices. The structure is located in Gulf Islands National Seashore Park in Gulf Breeze, Florida. Gulf Breeze is on a peninsula off of the Florida coast near the far western border of the state. The structure is sited in a clearing within a wooded area just north of Highway 98 (Gulf Breeze Parkway), as shown in Fig. 1. Trees from 6 to 8 m (20 to 25 ft) tall surround the clearing in which the structure is sited. The structure is assumed to correspond to an exposure category between B and C.

This is a single story, slab on grade structure, 13.3 m (44 ft) long by 8.5 m (28 ft) wide, with a floor-to-ceiling height of 3 m (10 ft). The structure has a hip roof which is constructed of clear-span engineered trusses spaced at 610 mm (24 in.) on-center. The roof trusses are made of Southern Pine 2×4 (50×100 mm) dimensional lumber, ranging in grade from #2 to Dense Select Structural, depending on member location. The roof is sheathed with 13 mm (1/2 in.) 4-ply CDX plywood decking, which is secured with 8d ring shank nails (length 60 mm, diameter 3.33 mm) spaced at 150 mm (6 in.) throughout. This met the International Residential Code [45] requirements for hip roofs exposed to 100 mph or greater wind speeds. Note that gable roofs have more stringent fastener requirements at edge locations. The roof pitch is 4:12, with 600 mm (24 in.) enclosed (box) overhangs on all sides and a mean roof height of 3.9 m (13 ft). Roof decking panel edges align on truss chords and are typically 4×8 (1.2×2.4 m) or 4×6 (1.2×1.8 m), as limited by the roof geometry. Wall studs are also spaced at 600 mm (24 in.) on-center, and directly align with the truss supports above (see Fig. 2). The interior ceiling and walls were later finished with 13 mm (1/2 in.) gypsum board (not shown in the figure). During construction, the house was instrumented with calibrated load cells between each truss reaction and the supporting wall (Figs. 2 and 3). Load cell locations are identified in a plan view of the structure by labels ending with "L" in Fig. 4. The dead load data were collected when the wind speed was negligible, and thus represent reactions due to the roof dead load only. Because the house is bi-axially symmetric, the 68 load cells can be grouped into 17 sets of four data each that have theoretically identical values. For example, the data from load cells S22L, S01L, N22L, and N01L (at the corners of the house; see Fig. 4) are in a symmetric set and theoretically should have the same reactions.

In addition to dead load reactions, the reactions found from hurricane level wind uplift pressures were examined. The field structure was instrumented with 76 pressure taps on the roof surface, with locations indicated with labels ending with "P" in Fig. 4. The pressure data made available for this study were recorded at 1 Hz from Hurricane Ivan. The instruments recorded the relative difference in pressure between the outer roof surface and roof interior. The data were continuously recorded from 9/10/2004 at 12:00 am until 9/23/2004 at 12:00 am. During that time, wind speed varied from 3.8 to 110 kph (2.4 to 68.6 mph). The peak wind speeds (averaged over 1-s gusts measured approximately 8 m above ground) 86–110 kph (53.9 to 68.6 mph) occurred from 9/16/2004 at 1:00 am to 9/16/2004 at 4:00 am (Greenwich Mean Time).

Fig. 2. House construction, interior view.